RETROFIT CONVERSION OF A LOW IMPEDANCE, SHORT PULSE ELECTRON BEAM ACCELERATOR TO HIGH IMPEDANCE, LONG PULSE OPERATION

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INTRODUCTION

An existing relativistic electron beam generator has been modified to increase its output pulse width from 100 ns to either 300 ns or 1,000 ns. In its original form, the generator consisted of a water insulated, 5.25 Ω coaxial pulse forming line (PFL) that discharged into a field emission diode through a low inductance gas-pressurized spark gap switch. A twenty stage Marx generator charged to the PFL to as high as 2 MV. At this voltage, an ~ 1 MV output pulse is developed into a matched load. An adjustable resistor shunting the PFL permitted matching its output to load impedances higher than 5.25 Ω.

The load impedance planned for the modified system is of the order of 100 Ω, and it is desired to deliver up to 800 kV to it. Important considerations are pulse shape, ability to reverse the modifications and, of course, reasonable cost—the latter being obtained by using as much of the original system as possible. The approach selected for the modification involved replacing the center conductor of the original PFL with one that is spiraled. This scheme provides long pulses within the same outer conductor used by the original short-pulse generator.

In addition to the pulse generator changes, the aim of the modification also required alteration of the interface between the generator output terminal and the new load. A new interface is required to deal with the longer pulse as well as to solve certain mechanical problems associated with the supporting the diode load. The interface and the diode are not discussed further here.

Testing of the pulse generator system has begun, and its performance will be compared here to that predicted by the modeling performed during the design process. At this stage of the test program, it has been determined that the impedance of the new PFL is significantly lower than what was anticipated. The reasons for the differences have not yet been fully resolved.

CONCEPT SELECTION

Two approaches were considered for achieving the longer pulse: a pulse forming network (PFN) based on the existing Marx generator, and a PFL with a spiraled inner conductor. The PFN approach would utilize a Guilliman Type A network of the form shown in Figure 1.

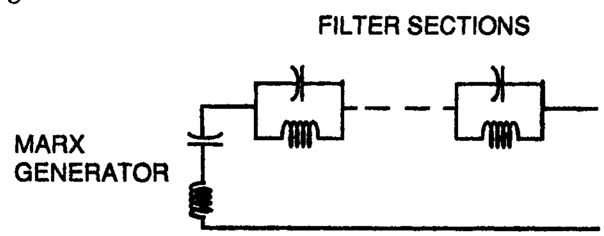

Figure 1. Guilliman Type A pulse forming network.

It involves the addition of one or more passive harmonic filter sections to the output of the Marx generator. At least two filters sections are required to generate and acceptable pulse shape.

While the PFN scheme appears to be feasible and perhaps even superior for the 1 μs case, it was rejected because of the complexity of changing the pulse width between the 1 μs and 300 ns cases. Unique values of every component are required for each pulse width. Nevertheless, in the case of a fixed pulse width of at least 500 ns or longer, the Type A PFN should be considered.

The chosen concept is the spiral transmission line PFL in the form of a coaxial line with a spiraled inner conductor as illustrated in Figure 2. It has the advantage of being adaptable to various pulse widths by just changing its physical length. Its principal disadvantage in this situation is that it must be charged in a time period that is long compared to the output pulse. This longer charging period affects the high voltage insulation in the pulse generator since electrical breakdown is time dependent.

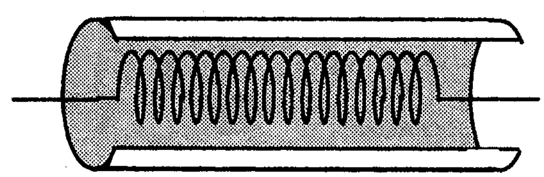

Figure 2. Spiral transmission line PFL.

The scheme for modifying the original generator is to replace its straight inner conductor with a spiraled one. The chief consideration in its design is electrical breakdown to the outer conductor during charge, and between turns of the spiral during discharge. Taking this

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into account, the highest practical impedance that can be realized within the available space is 85 Ω.

DESCRIPTION OF THE MODIFICATION

The existing coaxial pulse forming line is illustrated in Figure 3, while the new 300 ns and 1,000 ns PFL are shown in Figures 4 a and 4 b. The original pressurized gas spark gap is used to switch the new PFLs into their loads.

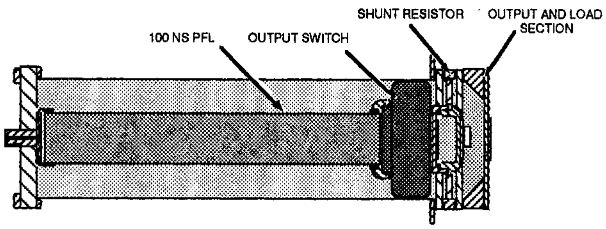


Figure 3. Original coaxial PFL.

Just at the output of the switch there is a shunt resistor that is adjusted to provide a matching load to the PFL in the case that the impedance of the diode should be higher. This resistor, a part of the original pulse generator, has the capability of absorbing the full energy of the pulse generator. It conveniently acts as a dummy load for testing.

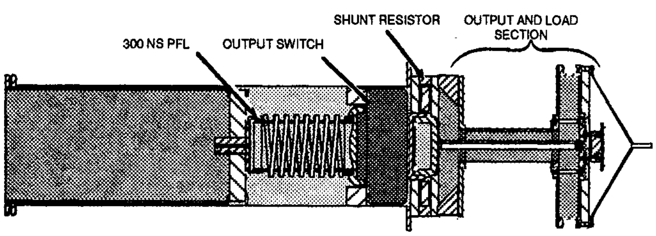


Figure 4 a. Modified 300 ns PFL.

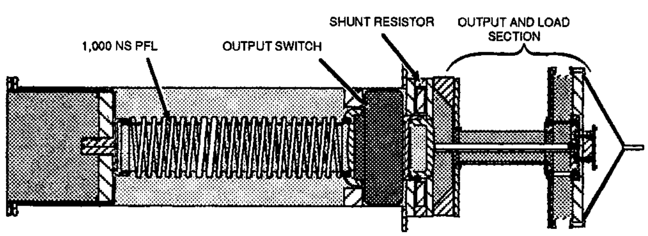


Figure 4 b. Modified 1,000 ns PFL.

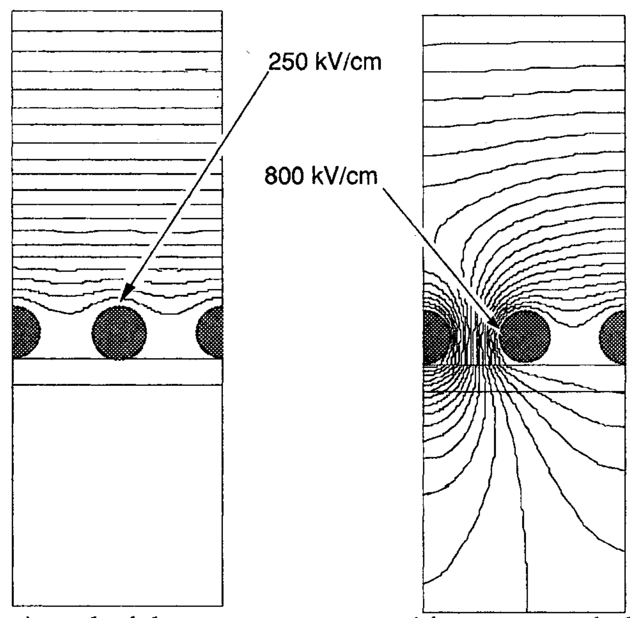
Pulse Forming Line—Each of the new PFLs is a coil of aluminum pipe that is wound around a polyvinyl chloride (PVC) pipe for support. The nominal diameter of the coil is 11 inches. The assembly is designed to fit the input connection of the existing output switch in the same way the existing 5.25 Ω inner conductor does. In general, the mounting of the new PFL is similar to the existing one, but since it is shorter than the original (for both pulse lengths), a special adapter is required for the oil-water interface between the PFL and the Marx generator.

The diameter of the conductor from which the coil is made is 1 inch, and the pitch of the coil is 1 turn/2 inches. The electrical transit time around one turn of the coil is about 26 ns. Based on the circuit modeling results, 7 turns will insure a flat-top pulse width of 300 ns while 1 μs requires 21 turns.

The maximum electric field on the surface of the coil at 1.6 MV charge is 250 kV/cm (see Figure 5). Using following relationship for impulse breakdown of water[1]

$$E = 0.56(\tau_{eff})^{-1/3}(\text{Area})^{-0.07}$$

The breakdown fields estimated to be 460 kV/cm for the 300 ns PFL, and 370 kV/cm for the 1 μs PFL. The 1 μs PFL works at a maximum of 68% of breakdown, while the 300 ns PFL is at 54%—both are conservatively low.



At peak of charge **After worst case fault**

Figure 5. Electric field on the inner conductor of the PFL

The worst case for electric field gradient occurs in the fault condition where the PFL discharges into a load that is a short circuit beginning at t = 0. The maximum field then appears between turns, and briefly reaches 800 kV/cm (also in Figure 5). Fortunately, it lasts for only about 25 ns so even this high value can be with stood safely. Nevertheless, the situation could be exacerbated by undamped oscillations within the pulse generator. Worst case fault mode ringing is too complex to model accurately and predict breakdown safety factors.

The impedance of the PFL was calculated from

$$Z = \frac{\tau}{C}$$

where: τ = the electrical transit time for the PFL
C = the PFL capacitance.

The transit time of the PFL is determined by its dimensions and the dielectric constant of water ($\varepsilon = 80$). To obtain the capacitance value, a computer program was used to calculate the electric field on the surface of the

inner conductor. The charge on the conductor is found from:

$$Q = \int E \bullet da$$

Then, dividing the charge by the potential yields the capacitance.

Using this method, the impedance of the modified PFL was calculated to be 85 Ω.

Marx Generator—The existing Marx generator has 20 stages, each with a nominal capacitance of 192 nF and a maximum working voltage of 100 kV. The internal inductance of the Marx is ~ 3 μH. Each stage has twenty four capacitors in a series-parallel combination an attribute that conveniently allows its capacitance to be varied by removing some of the capacitors. The results of circuit modeling based on a PFL impedance of 85 Ω showed that the capacitance needs to be reduced by one-half for the case of the 300 ns PFL.

Isolation Inductor—Not shown in Figure 4 is the inductor that connects the Marx Generator and the PFL. It slows the charging of the PFL so that the output pulse will not be unduly affected by the presence of the Marx generator. Two inductance values are used, 100 μH for the 300 ns PFL and 150 μH for the 1 μH PFL.

CIRCUIT MODELING

The modified pulse generator was modeled with PSpice[2] using the model show in Figure 6. The results for the 300 ns PFL are given in Figure 7, while Figure 8 is the calculated output pulse for the 1 μs PFL.

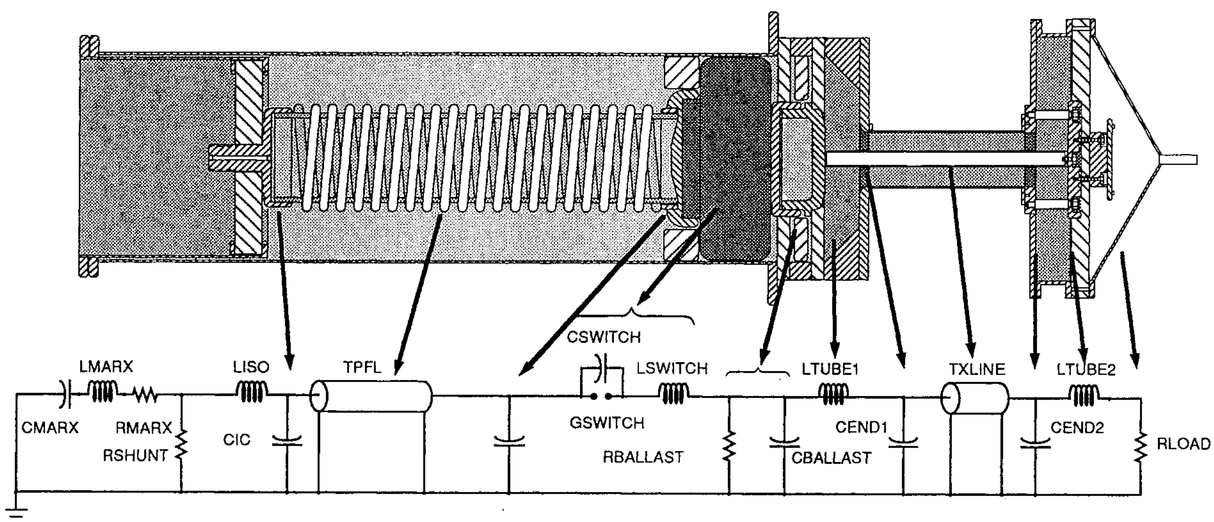


Figure 6. Circuit model of the modified pulse generator.

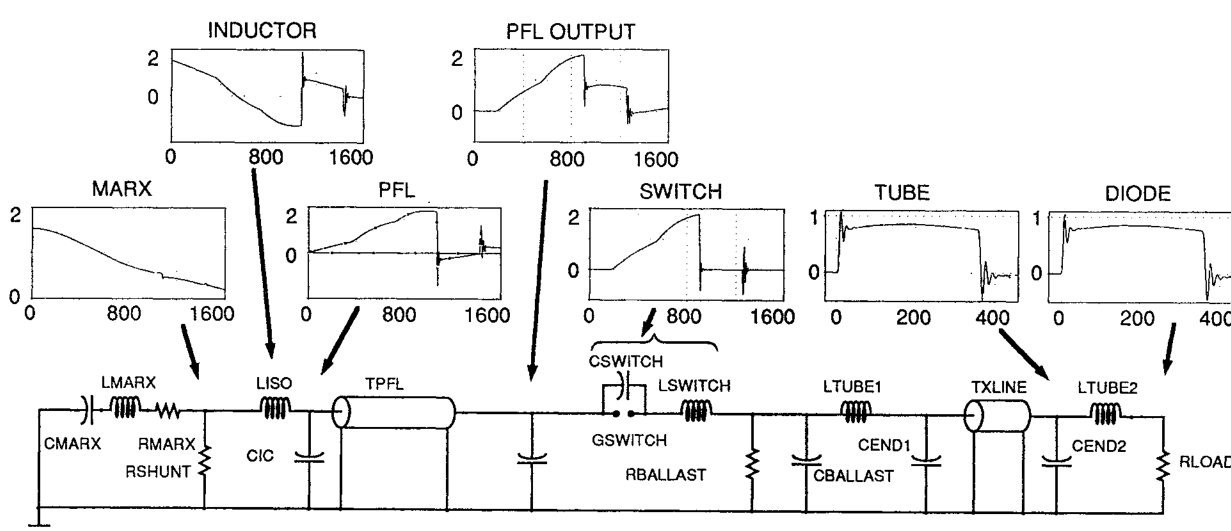


Figure 7. Calculated voltage waveforms for the 300 ns PFL case.

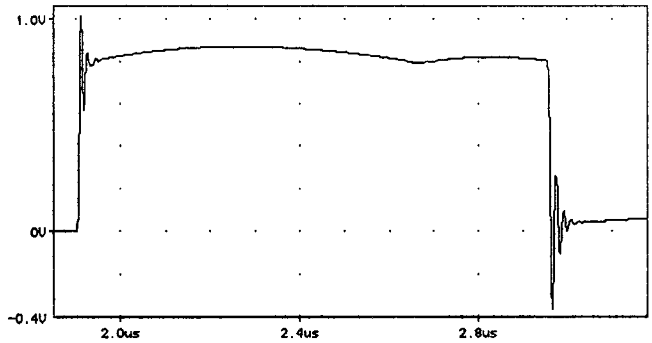


Figure 8. Calculate output voltage waveform for the 1,000 ns PFL case.

TEST RESULTS

Initial tests of the pulse generator were conducted using 300 ns PFL. The Marx generator stage capacitance was reduced from 192 nF to 96 nF in accordance with the modeling conclusions. The value of the shunt resistor at the output of the PFL was adjusted until the output waveforms indicated that it was matched to the impedance of the PFL—this being determined by analysis of the charging and output voltage wave forms. The surprising result of these tests was the discovery that, while the pulse length agrees with the design predictions, the impedance of the 300 ns PFL appears to be only 45 Ω rather than 85 Ω that was forecast.

Examples of the charging and output waveforms for the 300 ns PFL are given in Figures 9 and 10.

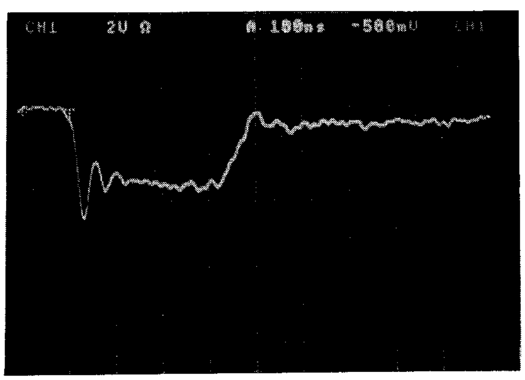


Figure 9. Output waveform from the 300 ns PFL

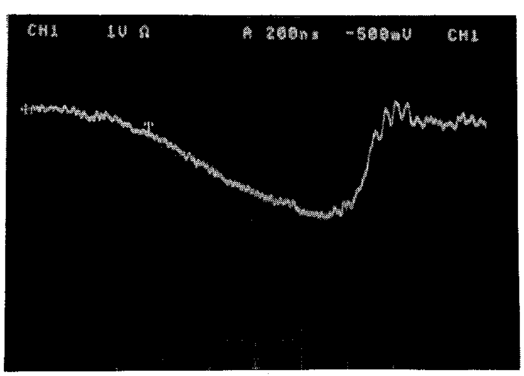


Figure 10. Charging waveform for the 300 ns PFL

Testing was also performed with the 1,000 ns PFL and it too has an impedance somewhat lower than 85 Ω; albeit, in this case it seems to be about 60 Ω. For expediency the tests conducted so far with the 1,000 ns PFL have been done without returning the Marx generator to its full capacitance configuration. Because of this, the output waveform is distorted and droops badly toward the end—a result that is predicted by the modeling. An example of the 1,000 ns output waveform is given in Figure 11.

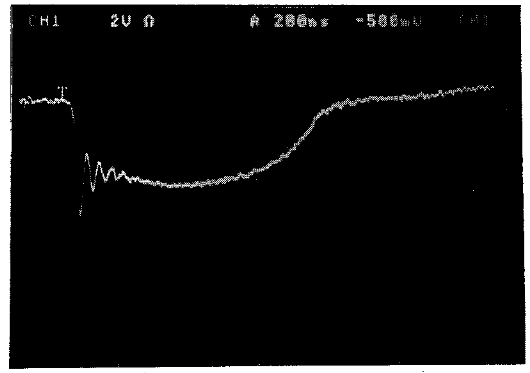


Figure 11. Output waveform from the 1,000 ns PFL

CONCLUSIONS

The limited testing performed so far indicates that the modified pulse generator will be able to meet the objectives that were established for it. The unexpectedly low PFL impedances, while not fully explained at this moment, are probably the result of a number of factors, each contributing to a portion of the discrepancy. The capacitance of the PFL is quite sensitive to dimensional tolerances, particularly the pitch of the spiral. Further, the capacitance calculation approximated the spiral by a series of rings. The effect of this approximation is to underestimate the capacitance, but not to the extent that has been observed.

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[2] PSpice, MicroSim Corporation, Version 5.0, September 1991, 20 Fairbanks, Irvine, CA 92718